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# Thermo-Optical Switching in Si Based Etalons

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The second experiment used a $Si/Si_3N_4$ film structure in which the index of the $Si_3N_4$ is approximately the square root of the index of the Si, and the optical thickness of the $Si_3N_4$ is an odd quarter wavelength multiple of the probe beam. This yielded a minimum in surface reflection.Based on an increase of the optical ...

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## Abstract

Thermo-optical switching in Si based etalons has been demonstrated in two device structures. In one experiment the switching time of a Si etalon has been reduced from ms to μs by choosing a probe beam of shorter wavelength in an external switching configuration[1]. The switching time has further been improved to the ns range by the use of a 1.06 μm Nd:YAG laser pump which is presumed to give rise to a thermo-refractive change in the Si etalon and at the same time the switching threshold energy has been reduced to ~ 1 μJ as compared to ~ 1 mJ for a $CO_2$ laser pump. In comparing Si etalons with thicknesses of 400 μm, 72 μm and 1.5 μm, we find that the 72 μm etalon exhibits the best behavior in terms of low threshold power, high speed and contrast. In addition, effects of the pump beam intensity on the signal pulse shape has been investigated which indicates a multiple interference fringe shift and transverse thermal relaxation dynamics.

The second experiment used a Si/$Si_3N_4$ film structure in which the index of the $Si_3N_4$ is approximately the square root of the index of the Si, and the optical thickness of the $Si_3N_4$ is an odd quarter wavelength multiple of the probe beam. This yielded a minimum in surface reflection. Based on an increase of the optical thickness with pump beam heating, a probe beam reflection has been switched out with a high contrast ratio (switched on/off) of 61:1.

Different structures using different pump beams are discussed and the restriction of the film optical thickness has been investigated.

## 1. Introduction

Si etalons have been shown to be bistable optical devices with radiation either at 1.06 $\mu m$ by band edge absorption[2] or at 10 $\mu m$ by lattice vibration absorption[3]. Experiments have been directed at reducing the switching power and time. The Self-Electro-Optical-Effect Devices (SEED) based on silicon greatly reduced the threshold optical input power at which bistability can occur[4]. The switching times of these Si based thermo-optical devices, however, are all in the range of ms, and require a high threshold switching energy (10's of mJ for pulse and mW's for cw laser).

In this study, we demonstrate thermo-optical switching in Si etalons with fast switching time and low threshold switching energy. Our previous experiments reported 1 $\mu s$ switching time from a thermally expanding Si etalon by using $CO_2$ pump pulses[1]. It was shown that the significant reduction in switching time, as compared to ms in the literature[3], was obtained by choosing a shorter wavelength probe beam in an external switching configuration, where a larger amount of the phase change could be caused by a smaller change in the etalon dimension. Recently, the switching time of our Si etalons has been further reduced to the ns scale by using a 1.06 $\mu m$ Nd:YAG laser short pulse pump, where we believe that a thermo-refractive effect dominates the switching rather than the thermal expansion in the etalon. Taking advantage of large thermo-refractive changes, the threshold switching energy has also been reduced to ~ 1 $\mu J$ (as compared to 1 mJ for $CO_2$ laser pump). In addition the etalon thickness was optimized to obtain improved switching characteristics, by considering the trade-off between optical absorption and thermal

relaxation. We have found that the switching dynamics which are determined by a multiple interference fringe shift under higher pump power, and a transverse thermal relaxation, are influenced strongly by thermal diffusion.

Also in this study $Si/Si_3N_4$ thin film structures have been investigated for optical switching. For these structures the surface reflection is designed to be a minimum where the index of the $Si_3N_4$ is approximately the square root of the index of the Si, and the optical thickness of the $Si_3N_4$ is an odd multiple of $\lambda/4$ for the probe beam. Pump beam heating increases the optical thickness of the $Si_3N_4$ etalon, thereby effecting an increase in the probe reflection. A high switching contrast ratio (ratio of switch on/off) of 61:1 was achieved. Both the switching rise time and the threshold switching energy are comparable to the bulk Si etalon. Different structures using different pump beams have been studied, and the dependence on the optical thickness of the $Si_3N_4$ thin film etalon has been investigated. The devices studied are both simple and cheap, hence thermo-optical switching in the $Si/Si_3N_4$ film structure might be promising for optical integration schemes. The operating principle for the $Si/Si_3N_4$ switch should also be applicable to other similar materials. Different thin film etalons can be chosen for a broad range of probe wavelengths.

## 2. Optical Switching in Si Etalons

### A. Experiments with Different Pump Beams

A simple expression to describe the interference mechanism for the etalon type of devices is given by

$$2nL\cos\theta = m\lambda \tag{1}$$

where n, L and $\theta$ are refractive index of the cavity material, cavity length and incident angle, respectively, and m is an integer. For a fixed incident angle, either a change in the cavity length, $\Delta L$, or a change in the index, $\Delta n$, can cause a phase change, $\Delta\lambda$, and result in an interference fringe shift. The switching would not take place until the $\Delta L$ or the $\Delta n$ yields a phase change of near a half wavelength. Thus, for this kind of a device, a shorter wavelength would require a smaller change of the optical length (nL), hence less time, to switch.

Our initial experiments[1] exploited an external switching configuration including a pump beam from a pulsed 10 $\mu$m $CO_2$ laser with a pulse duration of 100 ns and a 1.5 $\mu$m or 1.1 $\mu$m cw HeNe probe beam. The etalons used are 2x2 cm n-type Si with resistivity ~ 1 $\Omega$cm, with 2 surfaces polished, and with a thickness of ~ 400 $\mu$m. The Si etalon was aligned at a reflection minimum, i.e. transmission resonance, in order to enable the buildup of a coherent field inside the cavity. Efficient absorption of the pump energy in the Si lattice vibration region enables the etalon to expand and have a sufficiently large thermal shift for a short wavelength probe beam. The switching time obtained was ~ 1 $\mu$s which was faster by 3 orders of magnitude than self-switching $CO_2$ light[3]. The switching contrast ratio was 2:1 and the threshold switching energy was ~ 1 mJ.

In order to reduce thermal dissipative energy, a 1.06 $\mu$m Nd:YAG laser with a pulse width of 10 ns was used as the pump beam for the band edge absorption in Si. The sample used was a 400 $\mu$m thick Si etalon with a 1.1 $\mu$m probe beam and a Ge detector. The experimental set-up was same as that used with the 10 $\mu$m $CO_2$ pump laser. The Si etalon

was initially set in a reflection minimum. The YAG laser causes free carrier generation, heating and consequently detuning of the initial reflection minimum. The result is a rapid increase in reflection of the probe beam. As expected, the switching time has been further reduced to ~ 50 ns (which is the detector limit) with the 10 ns Nd:YAG laser pulse and the switched out 1.1 $\mu$m reflected pulse is shown in Fig.1. This is one order of magnitude shorter than with the 100 ns $CO_2$ pulse. Thus, it is predictable that one can obtain even faster switching time, with the use of an even shorter pump pulse. Also, it should be noticed that, the threshold switching energy for 1.06 $\mu$m pump beam was ~ 1 $\mu$J, or 3 orders of magnitude lower than that for 10 $\mu$m pump beam.

It appears clear that these two beams pump the Si etalon by different mechanisms. The 10 $\mu$m $CO_2$ laser light excites Si lattice vibrations, hence the energy dissipated inside the cavity generates heat and causes the thermal expansion of the cavity, i.e. $\Delta L$, which causes switching. On the other hand, 1.06 $\mu$m pump beam generates free carriers and induces a refractive index change, $\Delta n$, resulting in a phase shift. The typical Si parameters in the thermal expansion and the thermal refractive index are given by[2,5]:

$$\frac{\Delta n}{\Delta T} = 2x10^{-4}/^{\circ}C, \qquad \frac{\Delta L}{L} = 3x10^{-6}/^{\circ}C \qquad (2)$$

Based on these parameters and a phase change of $\lambda/2$, one can estimate that for the same etalon the switching energy required for 10 $\mu$m pump beam is higher than that for the 1.06 $\mu$m pump beam. For example, in order to obtain a phase change of $\lambda/2$ in a 400 $\mu$m Si etalon with 1.1 $\mu$m probe beam at normal incidence, the temperature rise in the etalon for the 10 $\mu$m pump is required to be ~ 58°C but only ~ 4°C for the 1.06 $\mu$m pump.

B. Experiments with Various Etalon Thicknesses

In order to optimize the switching characteristics, in terms of low threshold energy, high speed and contrast ratio, we have examined different Si etalons with thicknesses of 400, 72 and 1.5 $\mu$m for both 1.06 $\mu$m and 10 $\mu$m pump beams. The probe beam was 1.1 $\mu$m light. The 400 and 72 $\mu$m etalons are double sided polished Si crystal wafers, and the 1.5 $\mu$m etalon is a crystalline Si film chemically bonded onto a thin $SiO_2$ layer which is grown on a Si substrate. The $SiO_2$ layer is used to thermally isolate the Si thin film from the Si substrate.

In the switching experiments, the three etalons exhibited the same rise time, approximately same threshold switching energy, and a higher switching contrast ratio was observed for the thinner etalon. The fall time of the switched out signal was found to be greatly reduced as the etalon thickness decreased. These results shown in Table I indicate a trade-off between absorption and thermal diffusion. For the 10 $\mu$m pump beam, for example, the thicker etalon absorbs more energy and therefore expands more readily, but on the other hand, it has a larger thermal mass which takes longer to cool by thermal diffusion. The thinner etalon cavity allows more transmission which increases the cavity finesse[6], and therefore results in a higher switching contrast ratio. We found that the 72 $\mu$m etalon with 1.1 $\mu$m probe and 1.06 $\mu$m pump exhibits the best overall behavior: 1 $\mu$J threshold switching energy, 50 ns rise time, 400 ns fall time, and 4:1 contrast ratio. The 1.5 $\mu$m etalon did not show the highest contrast ratio as expected. A possible reason is due to the imperfect cavity which combines Si and $SiO_2$ layers, and the interface between Si and $SiO_2$ may lower the reflectivity thus the finesse. The failure of the 1.5 $\mu$m etalon to switch under the 1.06 $\mu$m pump light is probably due to insufficient absorption, with $\Delta n$ being too

small for the switching to take place.

C. Experiments with Various Pump Intensities

Previous work showed that a Si etalon can be tuned over several resonances of the cavity either with a cw laser via a thermal mechanism[1], or with a pulsed laser via a refractive index change[6]. In this paper, we report that the Si cavity tuning based on a thermal-refractive effect can be observed in the reflected probe beam with an external switching configuration. The refractive index varies both during and after the pump pulse and tunes the cavity over several resonances when the absorbed energy is higher than that required for a phase shift of $\lambda/2$. The reflected probe pulse shapes are modulated resulting in a number of peaks that depends on the pump energy.

The transmission of an etalon cavity is given as:

$$T = \frac{I_T}{I_o} = \frac{1}{1 + \frac{4R}{(1-R)^2}\sin^2\beta} \tag{3}$$

where $I_0$ is incident intensity, $I_T$ is transmitted intensity, R is the reflectivity of two surfaces and the phase shift $\beta$, similar to Eqn.1, is given by:

$$\beta = \beta_o + \frac{2\pi L}{\lambda}\Delta n \tag{4}$$

where $\beta_0$ is the initial phase of thc tuned etalon, and $\lambda$ is the wavelength of the probe beam. The reflection is a complement of the transmission with the absorption and the cavity loss, therefore, the reflection can also be described qualitatively with equation (3). Upon the pump beam illumination, the phase shift which is caused by the thermal-refractive index

change, $\Delta n$, is large, such that the probe beam passes through several resonance peaks. For these experiments we used a 400 $\mu$m Si etalon, a 1.1 $\mu$m probe beam from a HeNe laser and a pump beam from a 1.06 $\mu$m Nd:YAG laser. With initial detuning of the cavity to non-resonance, Fig.2(a), (b) and (c) show the probe pulses which exhibit one, two and multiple reflection minima, respectively, corresponding to the increasing pump intensities. The pump beam spots are the same sizes, the pump power is 1 kW, 5 kW and 26 kW for (a), (b) and (c), respectively.

From equations (3) and (4), we know that the optical length of the cavity changes by a half wavelength of the probe beam in between two reflection maxima or minima. The thermally induced index changes can thus be estimated from (b) as ~ $1.4 \times 10^{-3}$ with a 5 kW pump power, and from (c) as ~ $4.3 \times 10^{-3}$ with 26 kW pump power.

Another interesting switching dynamics effect which also depends on the pump intensity is the transverse thermal relaxation inside the Si cavity. Basically, a thermal change in absorption coefficient is associated with a thermal refractive index change. For the pump-probe beam configuration, the pump beam initially rapidly heats the illuminated spot and increases the absorption in the heated area. The temperature then drops rapidly due to the large transverse gradient. Finally, with the increasing probe beam absorption stimulated by the pump beam heating, a relaxation to higher temperature takes place.

To demonstrate this transverse effect on the switching dynamics, we used a tightly focused 1.06 $\mu$m pump beam and a 1.1 $\mu$m probe beam. Fig.3(a) shows the switched out signal pulse which first shows rapid increase in reflected intensity (increasing absorption) within 50 ns due to the fast heating of the Si etalon, and then this is followed by a return to a lower

reflection level, and then a slow relaxation to the higher reflection, indicating the transverse heat diffusion. The probe signal pulse with lower pump energy (two orders lower than that used in Fig.3(a)) is shown in Fig.3(b). The pump energy is insufficient to provide the heat for transverse diffusion, thus, the reflection quickly returns to the initial level after the rapid increase due to increasing absorption. A clean 10 $\mu$s signal pulse has been achieved.

## 3. Optical Switching in $Si/Si_3N_4$ film structures

### A. Theory and Structure Design

An optically transparent thin film with a refractive index $n_1$ deposited on a substrate with an index $n_2$, has a reflectivity given by[7]:

$$R = \frac{(\bar{n}_o-\bar{n}_2)^2\cos^2\delta + \left(\frac{\bar{n}_o\bar{n}_2}{\bar{n}_1} - \bar{n}_1\right)^2\sin^2\delta}{(\bar{n}_o+\bar{n}_2)^2\cos^2\delta + \left(\frac{\bar{n}_o\bar{n}_2}{\bar{n}_1} + \bar{n}_1\right)^2\sin^2\delta} \tag{5}$$

where $n_0$ is ambient index which is 1 for air. For non normal incidence there are two values of R, $R_p$ and $R_s$ each with a particular n value for the p and s light components. For the p component (polarization parallel to the plane of incidence) $\bar{n} = n/\cos\theta$, and $\bar{n} = n\cos\theta$ for the s component (polarization perpendicular to the plane of incidence), where $\theta$ is the angle of incidence. $\delta$, the phase difference between the two surfaces, again similar to Eqn.1, is given by:

$$\delta = \frac{2\pi n_1 d}{\lambda}\cos\theta \tag{6}$$

where d is the film thickness, $\lambda$ is the wavelength of the incident light. For simplicity, we assume a substrate with $n_2 = 4$ (Si is near this value), a set of the curves of reflectivity versus film optical thickness (index multiplied by thickness) at normal incidence are calculated and plotted in Fig.4. The curves show reflection minima at every odd quarter wavelength, where the reflectivity is given as:

$$R = \frac{\left(1 - \frac{n_1^2}{n_2}\right)^2}{\left(1 + \frac{n_1^2}{n_2}\right)^2} \tag{7}$$

The minimum goes to zero at the condition of $n_1 = \sqrt{n_2}$, i.e. for the curve of $n_1 = 2$.

Based on the thin film interference effect discussed above, we designed a $Si/Si_3N_4$ structure for which the index of the $Si_3N_4$ film (near 2)[8] is approximately equal to the square root of Si index (near 4)[8]. The structure is shown in Fig.5. A thermally grown 1 $\mu$m $SiO_2$ layer was used as thermal isolator on the Si substrate. A 10 nm Al layer was then evaporated on the $SiO_2$ before the deposition of the Si and $Si_3N_4$ layers. The Al layer is an external absorber, with the purpose of efficiently feeding back the transmitted pump beam energy. The 10 nm Al film reflects more than 90% of the IR pump light, and by being thin also avoids extra thermal capacitance. Both Si and $Si_3N_4$ films were deposited via plasma assisted CVD, and both the indices and the thicknesses could be controlled. The Si layer was ~ 1.5 $\mu$m which was thick enough to be opaque to the visible probe beam, i.e. optically, the probe

beam sees only the Si and the $Si_3N_4$ overlayer. Thus, the Si layer can be regarded as a substrate. The most restrictive dimension is the optical thickness of the $Si_3N_4$ thin film etalon. In order to achieve an initial reflection minimum, the optical thickness, $n_1d$, has to be odd quarter wavelength multiples of the probe beam. For this sample, named sample 1, the optical thickness is around $7\lambda/4$, where $\lambda = 6328$ Å, which is the probe beam from a cw HeNe laser. The pump beam was from the 10 $\mu$m pulsed $CO_2$ laser.

For comparison, sample 2 was also designed identical to sample 1 but sample 2 does not have an Al layer. Sample 2 was designed for a visible light pump beam which is completely absorbed in the Si layer, thus, an additional absorber is not needed.

B. Switching Characteristics

Different pump beams were chosen to optimize the switching performance. A 10 $\mu$m $CO_2$ pump beam for sample 1 utilizing the Al external absorber, and visible pump beams for sample 2 were found to be best. Comparisons between the two samples using both ir and visible pump beams were also carried out.

In the experiment where 10 $\mu$m pump beam and sample 1 were used, the 6328 Å HeNe probe was focused onto the sample with a 100 $\mu$m diameter spot, at slightly off normal incidence. The initial surface reflectivity is ~ 0.075% where the reflection is at the minimum. Upon illumination by the pump beam which was also focused to ~ 100 $\mu$m diameter, the heat generated in the Si layer which absorbed 10 $\mu$m light, transferred to the $Si_3N_4$ layer. The underlying $SiO_2$ insulating layer prevented excessive losses to the Si wafer. Energy feedback from the aluminum layer makes pumping more efficient. The index and the

thickness of the $Si_3N_4$ increase, thereby detuning the etalon away from the reflection minimum. A positive reflected signal pulse from the probe beam is therefore switched out. A high switching contrast ratio, 18.5:1 (on/off), was achieved. The threshold switching energy was ~ 1 mJ and the switching time was 1-2 $\mu$s. The switching characteristics are comparable to that of the 400 $\mu$m Si etalon but with the much higher contrast ratio.

In order to confirm the energy feedback from the external absorber, the aluminum layer, we tested sample 2 with the 10 $\mu$m pump beam. Sample 2 was not uniform in terms of film thickness, but two lowest reflection spots were pumped, their switching contrast ratio are shown in Fig.6. Compared to the contrast of 18.5:1 on sample 1 at the same minimum reflectivity, sample 2 has a lower contrast as 7:1. The aluminum layer enhances the switched signal by more than twofold.

For those samples with a $Si_3N_4$ layer directly on Si, that is without $SiO_2$, at the same surface reflectivity, 0.17% for example, and with the same pump power, the switched out signal displayed a much lower contrast ratio, less than 1.3:1, compared to 4.5:1 for sample 1. Also those samples required much higher switching threshold energy. This can be explained by considering that for the sample without the $SiO_2$ insulating film, the pump power is partly dissipated in the Si substrate which has large thermal mass and thus only a small part of the heat transfers to the $Si_3N_4$. For sample 1 and 2 the heat generated in the Si layer is blocked by the $SiO_2$, thus, a greater fraction of the heat transfers to the $Si_3N_4$.

In another experiment with sample 2, several visible light 10 ns pulsed pump beams were used, including a 530 nm green beam from a frequency doubled Nd:YAG laser, 635 and 640 nm red beams from a tunable dye laser pumped by the YAG laser. In particular, the 635

and 640 nm beams which are only a few nm different from the 632.8 nm probe HeNe light were utilized to demonstrate cascadeability of the $Si/Si_3N_4$ switches, i.e. a device is "cascadeable" when the output from one device is able to drive another device. Although the peak power of the dye laser is at 640 nm, it can be tuned to 632.8 nm as well. However, the pump beam scattering can not be eliminated at the photomultiplier if the wavelength is exactly the same as the probe light signal. Thus, the 635 and 640 nm lights were used for signal-noise separation. A monochromater was placed before the PMT to eliminate the 635 and 640 nm scattered light.

The reflected signal switched by the 640 nm pump light displayed a high switching contrast ratio of 61:1 with a low switching energy of ~ 80 $\mu$J. The threshold switching energy was ~ 20 $\mu$J. The rise time was as fast as 20 ns, and the fall time was 3 $\mu$s. Typical switched out signals from the 632.8 nm probe and a 640 nm pump pulse are shown on Fig.7. Since the Si layer with a thickness of 1.5 $\mu$m is thick enough to completely absorb visible light, the $Si/Si_3N_4$ structures using the visible pump light sources do not need an extra external absorber. The experimental results proved this prediction with sample 1 and sample 2 yielding same switching performance under the same conditions.

The key ingredient in order to achieve high contrast and efficient switching, is the closeness of the optical thickness of the $Si_3N_4$ film to $\lambda/4$ of the probe beam. The question is, how much deviation could be tolerated? It is fortuitous that sample 1 is not quite uniform, so that the surface reflection varies as the probe beam scans across the sample and this variable thickness enabled us to investigate the tolerance. Fig.6 shows a plot of the switching contrast ratio versus reflectivity using sample 1 and the 10 $\mu$m pump beam. The different

reflectivities are from different $Si_3N_4$ thicknesses found at different locations on the sample. The contrast drops exponentially as the reflectivity increases, and at a reflectivity of 7.5% the contrast ratio is one indicating that no signal was observed. Sample 2 with the visible pump beams showed qualitatively the same behavior as Fig.6. If we consider $n_1 = 2$ and the curves in Fig.4, we see that 7.5% reflectivity (0.075) is near a minimum, yet there is no signal. Thus the $Si_3N_4$ thickness must be more closely controlled to further reduce the initial reflectivity. However, modern CVD techniques for Si and $Si_3N_4$ films are probably adequate to achieve the necessary control of the film index and thickness. Also, one can choose different optical thicknesses of $Si_3N_4$ film to match with different probe wavelengths, as desired. Thus the Si/$Si_3N_4$ structure seems promising for optical integration schemes.

The advantages for the Si/$Si_3N_4$ structures are obvious: controllable deposition, low cost, high switching contrast ratio and cascadeability. However, the switching efficiency, i.e. output signal intensity versus input probe intensity, is low due to the initial reflectivity minimum. It would be useful to find more absorptive and/or nonlinear thin films with appropriate index suitable for this kind of Si based device. If optical excitation can occur directly in the film rather than in heating the substrate, the switching efficiency may be greatly improved. Also, the principle of the Si/$Si_3N_4$ device can be applied to other materials. A broad spectral range can be covered by choosing different film and substrate materials as desired. For example, the Si/$Si_3N_4$ structure may not work with a near infrared probe light due to the transmission of the Si layer, hence one needs to use other narrow bandgap semiconductors that are infrared opaque.

## 4. Conclusions

We have studied the thermo-optical switching in Si based etalons, including Si etalons and $Si/Si_3N_4$ film structures. By varying the pump beam wavelength and the pulse width, the etalon thickness and the pump beam intensity, we have investigated the switching characteristics for the Si etalons. The switching rise time has been reduced from ~ 1 $\mu$s to ~ 50 ns by the use of the 10 ns Nd:YAG laser pump pulse. Based on a thermo-refractive mechanism, the switching threshold energy has also been reduced to ~ 1 $\mu$J compared to the previous ~ 1 mJ. Among the different etalons with thicknesses of 400 $\mu$m, 72 $\mu$m and 1.5 $\mu$m, we find that the 72 $\mu$m etalon exhibits the best behavior in terms of low threshold power, high speed and contrast. In addition, we have investigated the pump power dependence of the signal pulse shape which indicates multiple resonances and transverse thermal relaxation dynamics.

From our work, it has been shown that the switching time and the threshold energy for the Si etalons are not intrinsic, but depend on the pulse width of the pump beam and the switching mechanism. It is predictable that one can obtain even faster switching times, if shorter pump pulses are used. In order to switch out one clean probe pulse, the pump intensity needs to be controlled to avoid multiple resonance and transverse heat diffusion.

Probe and pump beams can have the same wavelength for the Si etalons in order to achieve cascadeable switches. Our results show that the etalons have better performance by using a shorter wavelength probe beam and a Nd:YAG short pump pulse. Reports of optical bistability in Si with 1.06 $\mu$m radiation[2] will likely lead to better switching characteristics with

the use of a cw Nd:YAG laser as probe and pulsed as the pump.

A novel optical switch using a thin film interference effect has been demonstrated with $Si/Si_3N_4$ structures. The experimental results show that a $SiO_2$ isolating layer and an aluminum external absorber in the structure can enhance the switched out signal and lower the switching threshold energy. The device cascadeability and structural restrictions have been investigated. Advantages for the $Si/Si_3N_4$ are fourfold. First, Si and $Si_3N_4$ film are cheap, easily deposited and with well known properties. Second, a broad spectral range for visible probe beams can be covered by choosing suitable optical thicknesses for the $Si_3N_4$ film, and the device can be made cascadeable. Third, the switching contrast ratio can be high starting from an initial reflection minimum. Finally, since the structure only uses conventional microelectronics processing, it is promising for optical integration schemes.

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Figure Captions

Fig.1 Switched out 1.1 $\mu$m probe light signal using a 10 ns pulse of 1.06 $\mu$m light as the pump beam.

Fig.2 Probe signal pulses exhibiting (a) one, (b) two, and (c) multiple reflection minima. Sample was a 400 $\mu$m thick Si etalon, the probe was 1.1 $\mu$m light and the pump was 1.06 $\mu$m.

Fig.3 (a) Probe pulse shape indicates a transient transverse heat diffusion, (b) the clean signal pulse switched by the lower pump energy. The sample was a 400 $\mu$m Si etalon excited by a 1.06 $\mu$m pump and the probe beam was 1.1 $\mu$m.

Fig.4 A set of reflectivity curves as the function of film optical thickness $n_1d$ for various film indices, assuming the Si substrate has an index equal to 4 and $\lambda$ = 6328 Å.

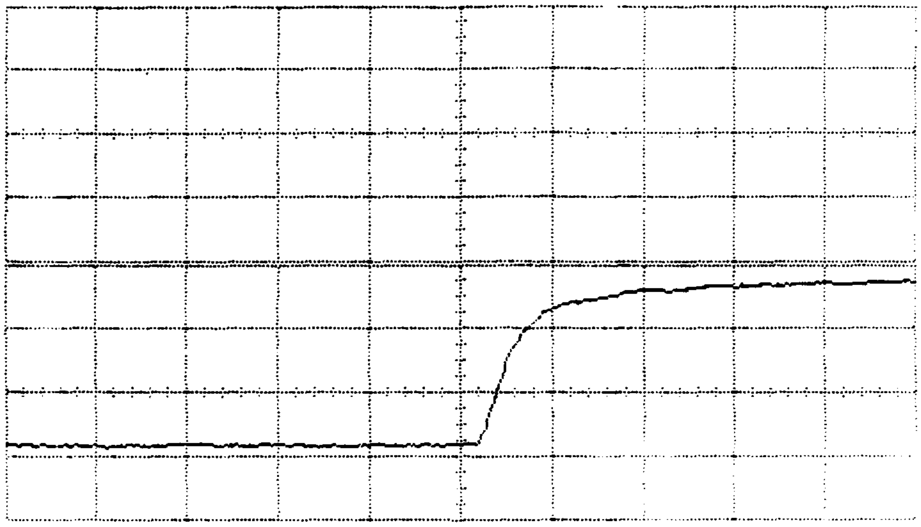
Fig.5 A schematic of the $Si/Si_3N_4$ structure for sample 1.

Fig.6 A plot of switching contrast ratio versus reflectivity for the $Si/Si_3N_4$ device termed sample 1 with the Al absorbing layer. The open circles are the data for sample 2 without the absorbing layer.

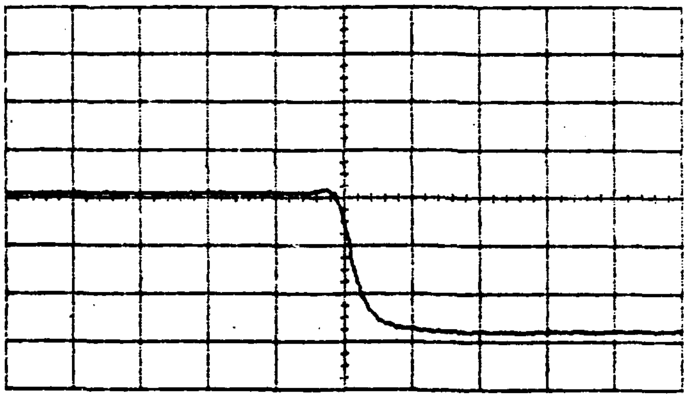
Fig.7 A typical switched out signal from 632.8 nm probe and a 640 nm pump pulse for the $Si/Si_3N_4$ structure.

Table I. Comparison of switching characteristics by varying pump beams and etalon thicknesses with 1.1 $\mu m$ probe beam

| Pump Beam Wavelength | Etalon Thickness | | | Threshold Switching Energy | Signal Contrast Ratio |
|---|---|---|---|---|---|
| | 400 $\mu m$ | 72 $\mu m$ | 1.5 $\mu m$ | | |
| 10 $\mu m$ | rise time ~ 1 $\mu s$ | ~ 1 $\mu s$ | ~ 1 $\mu s$ | ~ 1 mJ | 2:1 - 3:1 |
| (100ns pulse) | fall time ~ 5 ms | ~ 40 $\mu s$ | ~ 6 $\mu s$ | | |
| 1.06 $\mu m$ | rise time ~ 50ns | ~ 50 ns | N/A | ~ 1 $\mu J$ | 3:1 - 4:1 |
| (10 ns pulse) | fall time ~10 $\mu s$ | ~ 400ns | N/A | | |

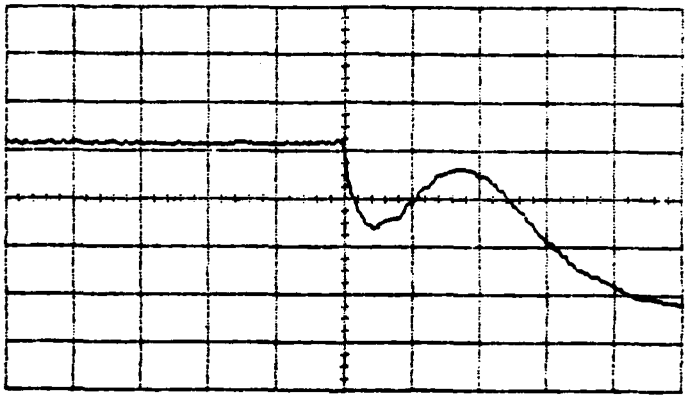


**100 ns/div**



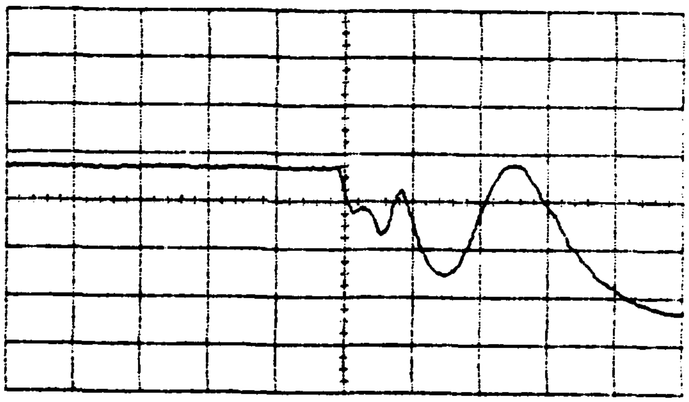
**200 ns/div**

**(a)**



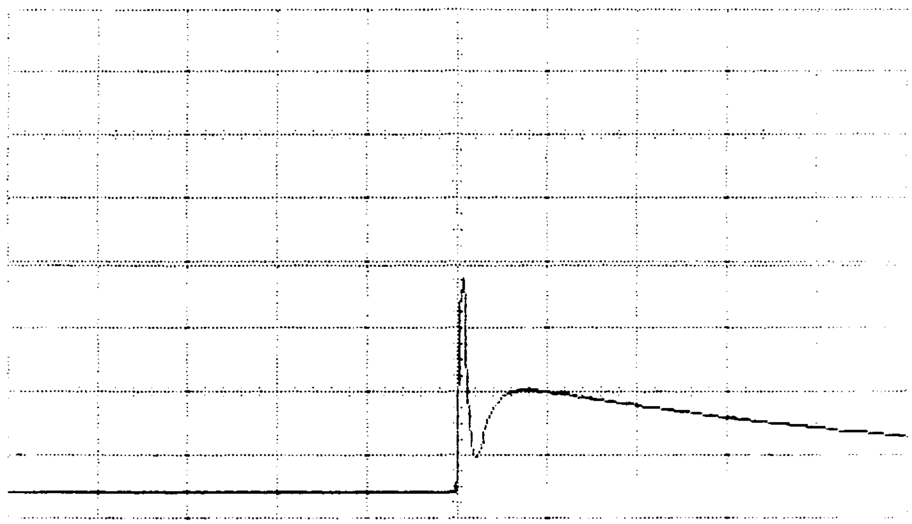
**200 ns/div**

**(b)**



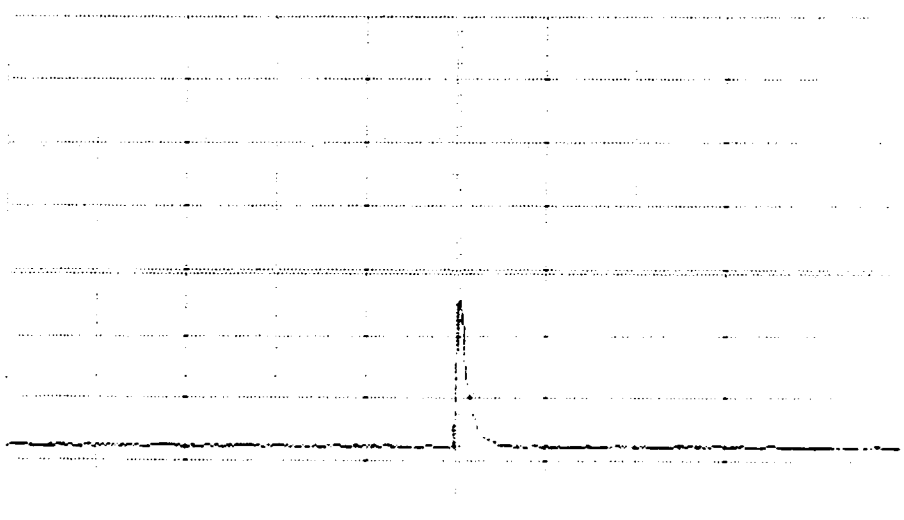
**200 ns/div**

**(c)**



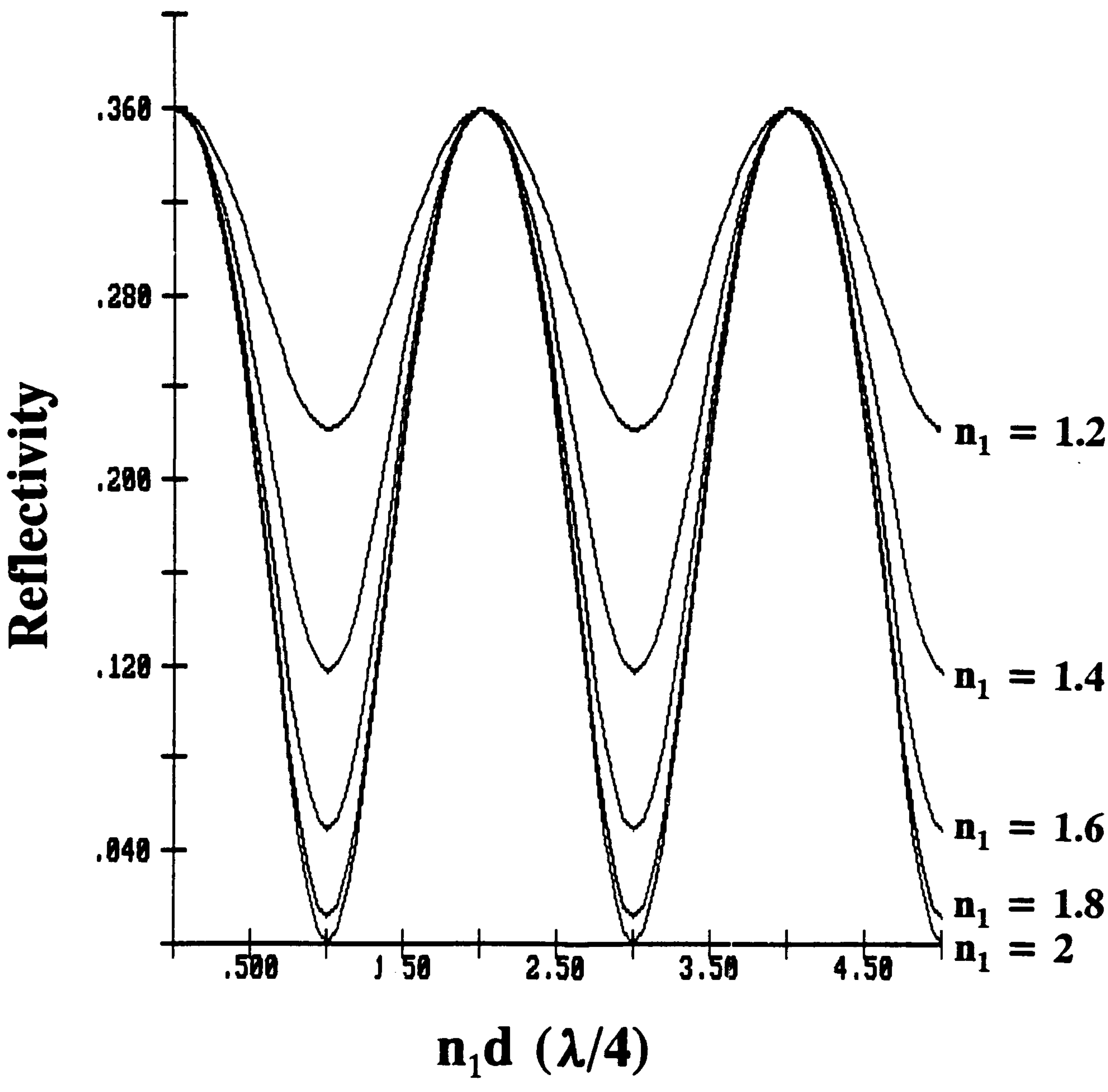
100 μs/div

(a)

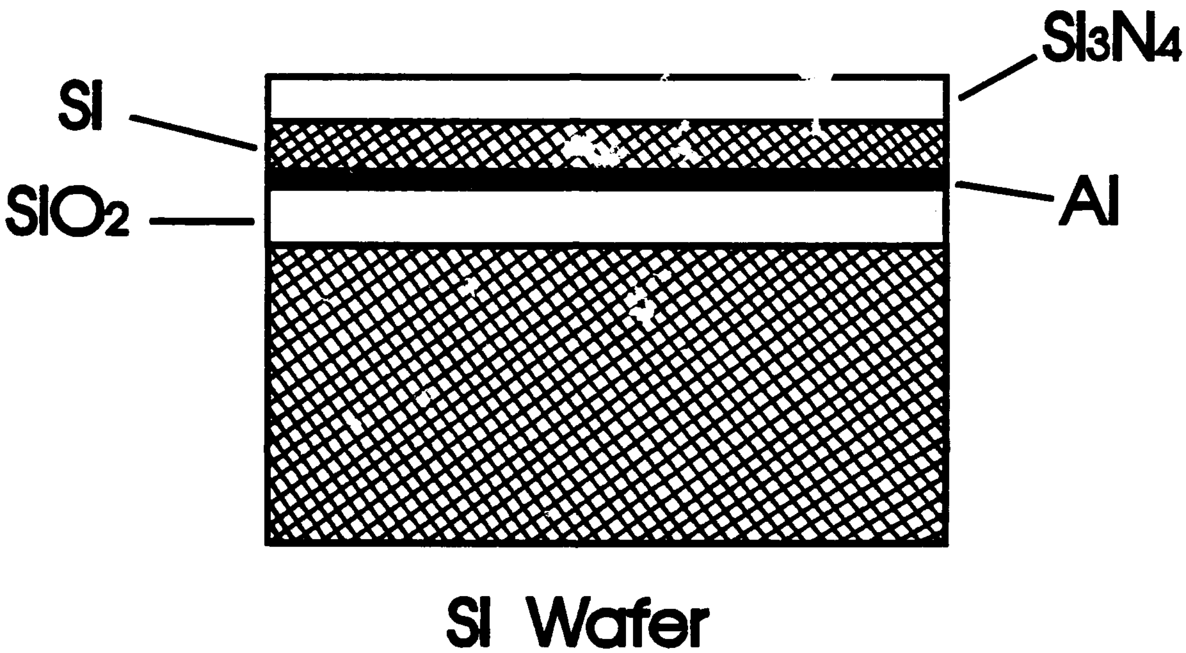


100 μs/div

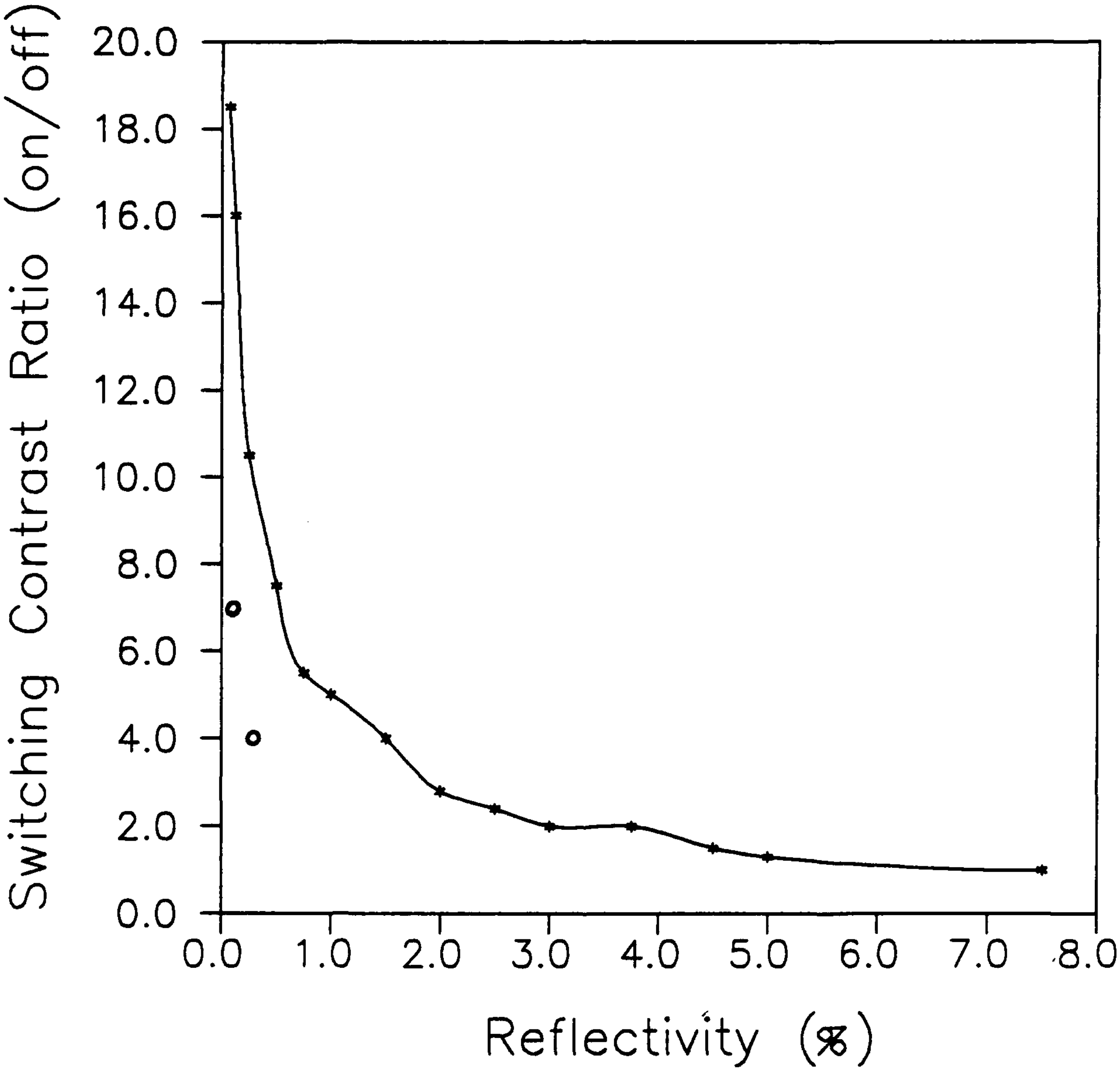
(b)

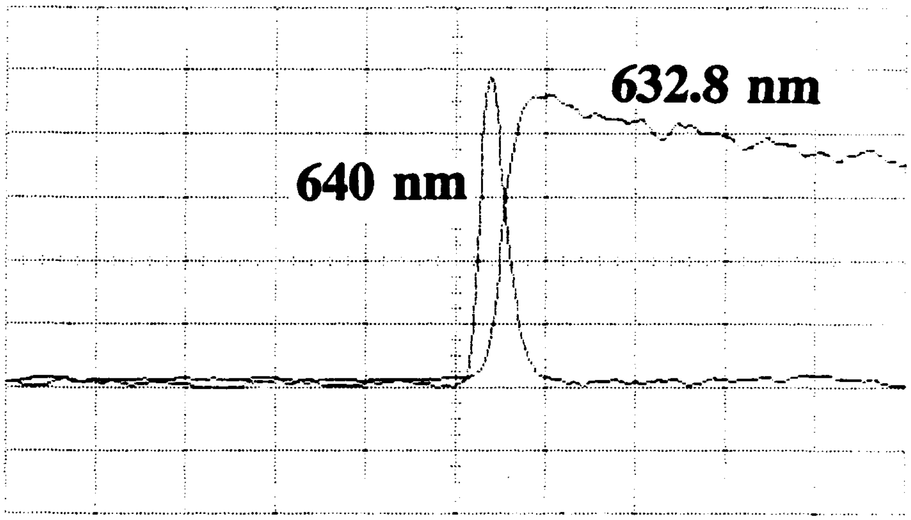


Reflectivity
.360
.280
.200
.120
.040
.500
1.50
2.50
3.50
4.50
n1d (λ/4)
n1 = 1.2
n1 = 1.4
n1 = 1.6
n1 = 1.8
n1 = 2



$Si_3N_4$
Si
Al
$SiO_2$
Si Wafer


Switching Contrast Ratio (on/off)
20.0
18.0
16.0
14.0
12.0
10.0
8.0
6.0
4.0
2.0
0.0
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Reflectivity (%)




50 ns/div